To Mars and Back: 2002-2020
Ballistic trajectory data for the Mission Architect

Steve Matousek† and Andrey Sergeyevsky††

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† Member of Technical Staff, Mission and Systems Architecture Section, Jet Propulsion Laboratory, Pasadena, CA, Senior member, AIAA, Member, AAS
†† Member of Technical Staff, Navigation and Flight Mechanics Section, Jet Propulsion Laboratory, Pasadena, CA

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Abstract

Future Mars missions require planning years in advance. In order to make these missions affordable while reducing mission risk, technology developments need to be structured to satisfy the mission architecture. Basic mission architecture questions that drive technology developments must be answered many years before a mission launches. These trajectory data for ballistic Earth to Mars and Mars to Earth trajectories span the years 2002 through 2020. Examining these data enables high level architecture construction for Mars missions. This paper includes a large format (60" X 36") chart of mission design data. Finally, we illustrate the use of these trajectory data for a propulsive capture case, an aerocapture case, and a sample return case.

Why generate these data?

The Mars Surveyor Program explores Mars in a logical fashion, governed by science strategies and the limitations of launching a payload to Mars. The current program includes two launches of Delta 7425 launch vehicles, one for an orbiter and one for a lander in each of the 1998, 2001, and 2003* launch opportunities. In November, 2004, a Mars Sample Return mission launches on a larger launch vehicle such as a Delta 3 or Atlas IIAR. After that mission, the current planning set becomes much more uncertain.

Planning future missions for 2007 and beyond requires trajectory data for the Earth-Mars and Mars-Earth opportunities. Published earlier trajectory data sets spanned the years 1990-2005 and 2015-2026[1,2]. However, these data did not examine type 3 or 4 trajectories or Venus gravity assists. This trajectory data set constitutes a thorough search of feasible ballistic trajectories for space transport to and from Mars for the first two decades of the new millennium.

Methods and Tools

The first problem in any trajectory search is to find a good guess with which start the search. For the initial guesses of the non-Venus flyby cases we use "pork-chop" plots of C_3 contours plotted over a launch date arrival date grid (see Figure 1).[1]

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* The 2003 mission includes a communication only orbiter, possibly launched on a smaller launch vehicle like the Taurus XLS or Athena II. Another option is to launch the orbiter and lander with rover together on a Delta 7925 launch vehicle. The 2003 orbiter then acts as the cruise stage for the 2003 lander with rover.

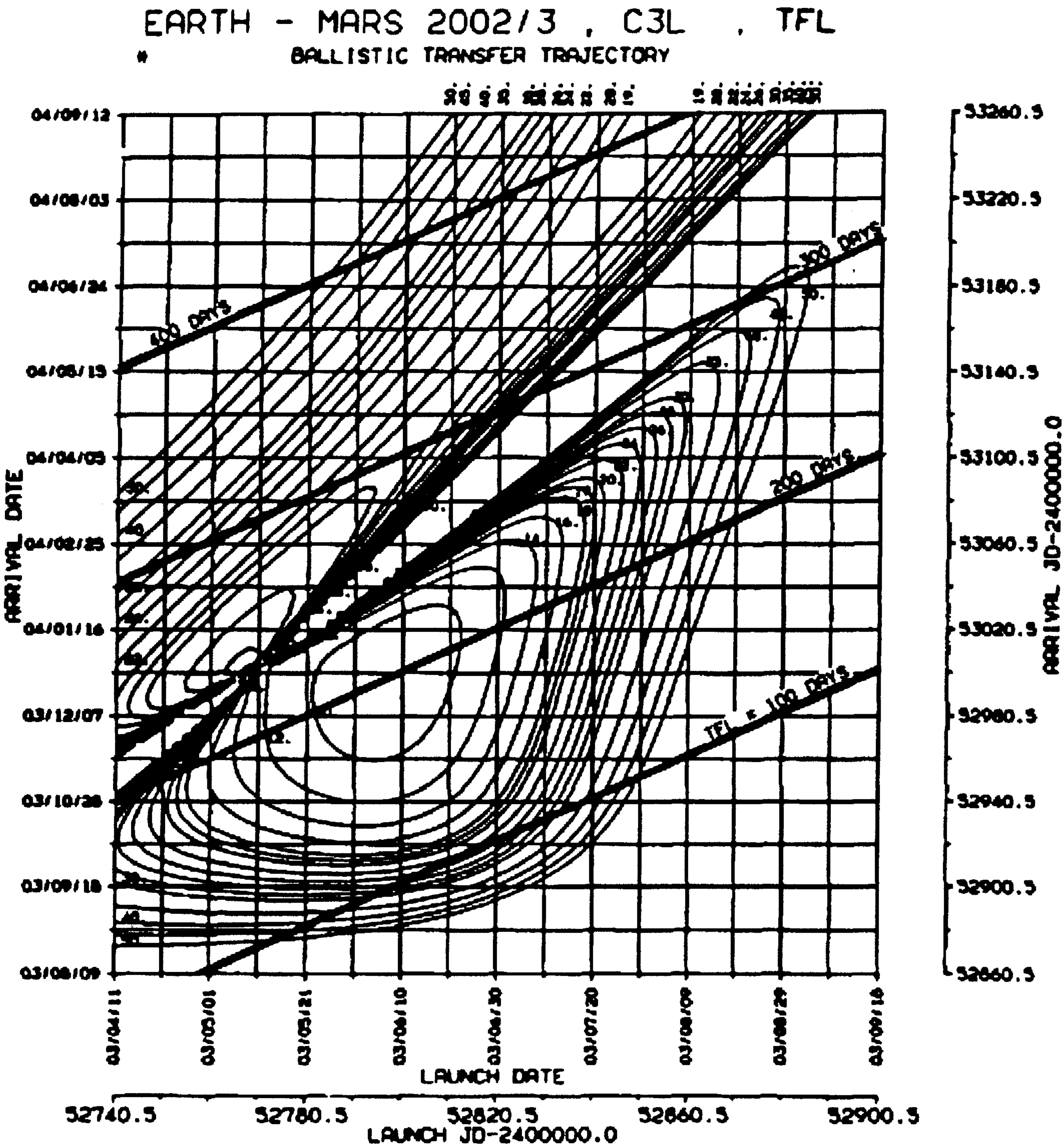

Figure 1 - Earth to Mars “pork chop” plot of launch C3 contours on a launch date and arrival date grid

After a suitable guess at launch and arrival date is determined, the initial conditions feed into Jet Propulsion Laboratory (JPL) software QUICK [3]. QUICK has a function called C3MIN which searches for the minimum energy solution given the launch planet, arrival planet, estimates of launch and arrival dates, the number of complete revolutions in heliocentric space, and a flag describing the type of energy optimization. In our case, we set the flag for a minimum launch energy (other options are minimum arrival energy, minimum of launch and arrival energy, and minimum of launch and arrival ΔV). The output heliocentric orbit data is the basis for the chart of trajectory data (figure 2).

For the Earth-Venus-Mars gravity assist trajectories we use a slightly different technique. First, a search is performed for type 1 and 2 trajectories to Venus from Earth launch using C3MIN. Second, perform a search for Venus to Mars type 1 and 2 trajectories. Then, input these dates as an initial guess to JPL multi-conic trajectory optimization software MIDAS. MIDAS outputs the launch date and arrival date for the minimum launch energy after adjusting the initial guess. The trajectory chart contains MIDAS output values for Venus gravity assists.

Trajectory Data

This data encompasses the following ballistic trajectories:

1) Earth to Mars type I - 4
2) Mars to Earth type I - 4
3) Earth - Venus - Mars type I and II

Mars - Venus - Earth trajectories are not included due to inherently higher Mars ΔV and Earth arrival velocity. The high inherent Earth arrival velocity is unacceptable for current and near-future thermal protection systems.

For any given type 3 or 4 trajectory there are two solutions per type. There is a type 3+ and a type 3-. And, for type 4, there is also a 4+ and 4-. The plus refers to outbound arrival planet conditions. Conversely, the minus refers to inbound arrival planet conditions (see figure 3).

Assumptions

Data are included for feasible trajectories only. For this data set, feasible means that C_3 is less than 25 (km^2/s^2). The launch energy was the only parameter minimized. It is also possible to minimize arrival velocity or the total energy involved in the ballistic trajectory (launch and arrival), but this requires some knowledge of the type of arrival. For instance, propulsive capture nearly always requires a minimum arrival velocity, while aerocapture can tolerate higher arrival velocities.

Also, these trajectories are provided only for the optimum launch day of each departure opportunity. Providing for a sequence of allowable launch days (launch period) will always increase the required launch energy. Launch periods can also lead to problems with declination of the launch asymptote exceeding the latitude of the launch site. These data should be used only as a guide. For deeper understanding of a given opportunity, additional trajectory and mission analyses must be done.

	Activity Name	TYPE	C3	DLA	V∞ arr	Dec Arr Asym	Start Date	Finish Date	02 03 04 05 06 07 08 09
1	2002 Earth to Venus Venus to Mars	1 1	12.3	25.3	 7.2	 -18.8	8/6/02 12/16/02	12/16/02 6/9/03	175 132
2	2003 Mars to Earth	2	9.6	-25.3	3.3	37.7	2/26/03	11/12/03	259
3	2003 Mars to Earth	1	7.4	-24.1	3.0	31.6	4/18/03	11/10/03	206
4	2003 Earth to Mars	2	12.7	-3.8	2.8	6.2	5/9/03	12/29/03	234
5	2003 Earth to Mars	1	8.8	-6.2	2.7	6.8	6/7/03	12/26/03	
6	2004 Mars to Earth	4-	6.4	2.6	4.2	11.6	3/8/04	8/2/06	877
7	2004 Mars to Earth	3-	6.5	38.3	5.6	-3.4	3/26/04	6/1/06	797
8	2004 Earth to Venus Venus to Mars	2 1	20.1	-8.8	 8.4	 -18.0	5/31/04 11/16/04	11/16/04 4/3/05	138 169
9	2004 Mars to Earth	3+	10.6	26.0	8.5	9.8	6/5/04	5/20/06	714
10	2004 Earth to Mars	4-	8.9	31.4	2.8	-26.6	11/14/04	2/4/07	812
11	2004 Earth to Mars	3+	9.4	-1.4	5.4	-11.1	12/16/04	12/20/06	734
12	2005 Mars to Earth	1	13.6	-28.0	3.7	5.1	6/28/05	1/6/06	192
13	2005 Mars to Earth	2	13.2	0.6	3.8	-38.9	7/8/05	3/31/06	266
14	2005 Earth to Mars	1	15.9	34.8	3.2	-8.6	8/10/05	2/22/06	196
15	2005 Earth to Mars	2	15.4	12.5	3.5	25.4	9/2/05	10/11/06	404
16	2006 Mars to Earth	4-	5.7	-2.2	5.1	24.2	4/2/06	9/2/08	884
17	2006 Mars to Earth	3-	6.0	39.4	5.8	1.7	4/13/06	6/22/08	801
18	2006 Mars to Earth	3+	7.5	25.5	7.5	12.7	6/4/06	6/16/08	743
19	2007 Earth to Mars	3+	9.0	-24.3	5.5	-2.2	1/11/07	12/18/08	707
20	2007 Earth to Mars	4-	8.7	-0.1	6.0	-28.1	2/15/07	6/11/09	847
21	2007 Mars to Earth	2	10.2	7.4	2.9	-48.7	7/21/07	4/29/08	283
22	2007 Mars to Earth	1	14.2	-15.9	4.4	-1.7	7/31/07	2/29/08	213
									02 03 04 05 06 07 08 09

Figure 3 - Trajectory Data subset from 2002-2010

<u>Column definitions</u>

C_3 = twice the excess launch energy in km^2/s^2

DLA = declination of the launch asymptote in degrees

V_∞ arr = arrival planet speed in km/s

Dec Arr Asym = Declination of the arrival asymptote in degrees with respect to the arrival planet equator of date

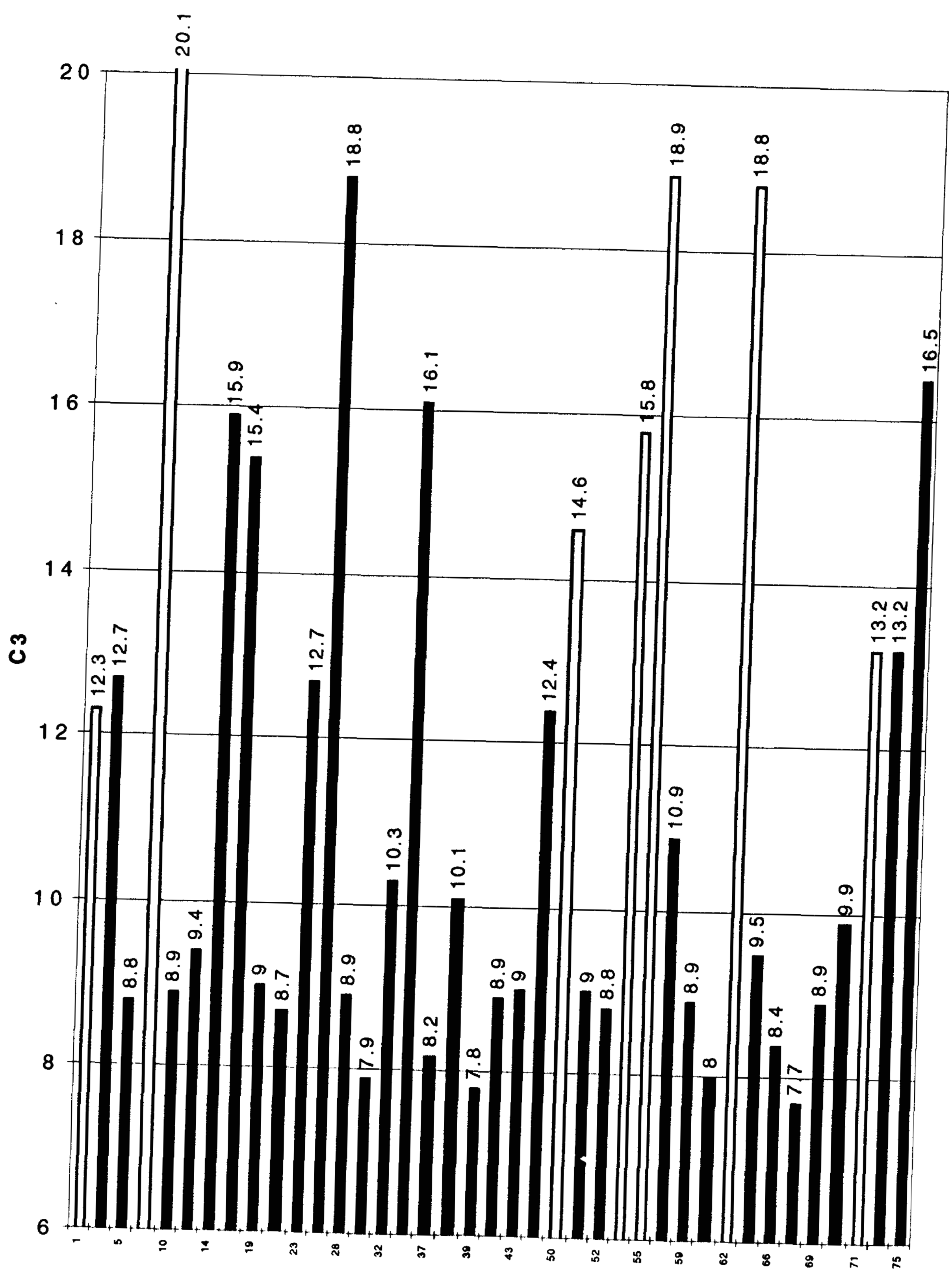

Figure 4 - C_3 of Earth to Mars trajectories (Venus flybys in outline)

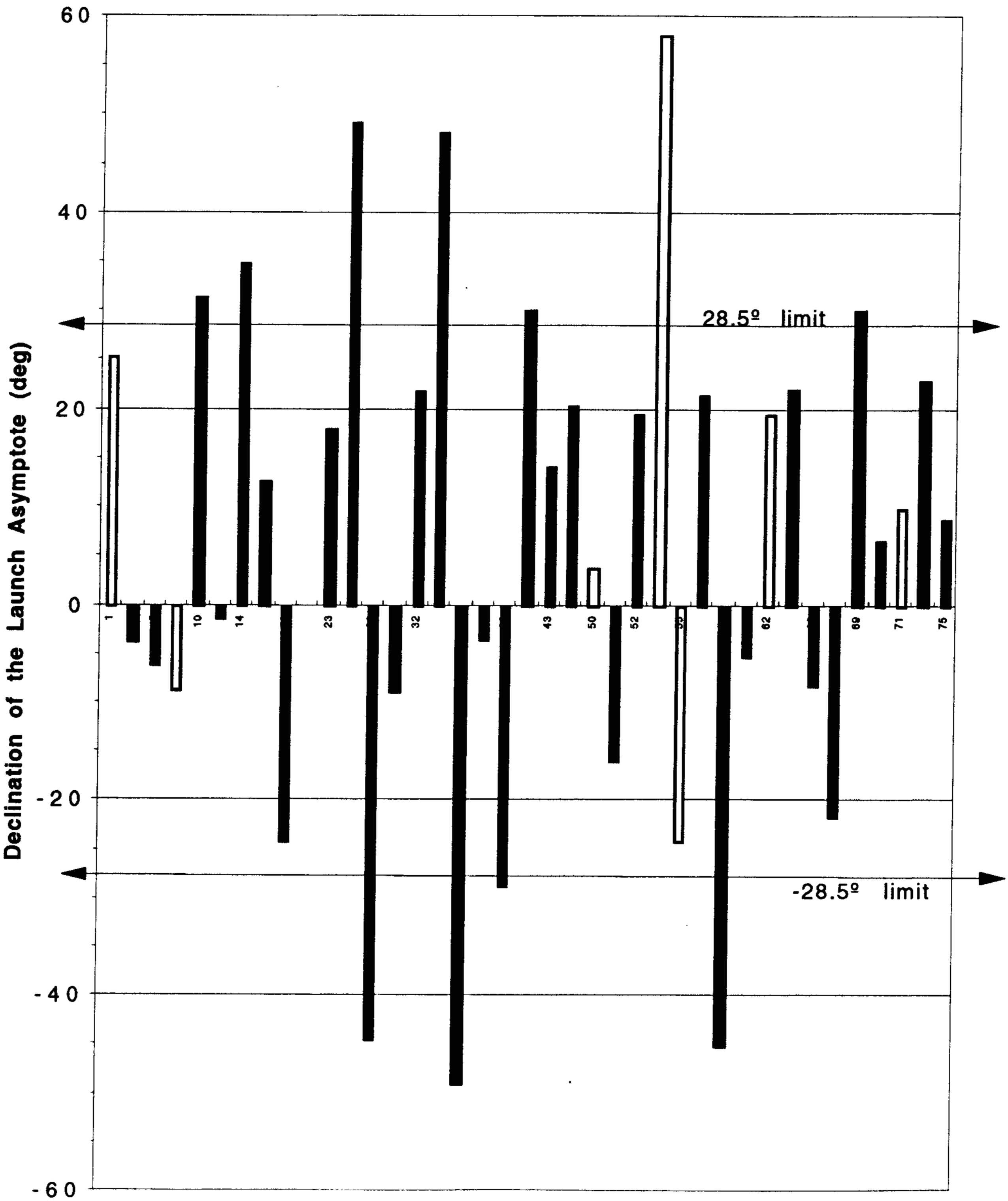

Figure 5 - Earth to Mars Declination of Launch Asymptote (Venus traj outlined)

General Observations of Trajectory Data

(insert figure of propulsive capture, aerocapture, and sample return regions here)

Good propulsive capture opportunities

Propulsive capture requires a large ΔV maneuver near the arrival planet. This maneuver is generally in excess of 1 km/s. Because of the large ΔV required, it is necessary to minimize the arrival velocity. The trajectory data are optimized for minimum launch energy and not for minimum arrival velocity. Even so, the values of arrival V_∞ given in the chart give an indication of the suitability for propulsive capture. In general, the arrival V_∞ will not decrease by more than a few tenths of a km/s for trajectories optimized for this parameter.

(Insert figure of arrival $V\infty$ here)

Good aerocapture opportunities

The Mars Surveyor 2001 mission will be the first planetary mission to use aerocapture. Aerocapture is useful when the arrival V_∞ cannot be reduced below about 3 km/s. Below this threshold, the mass and complexity of the aerocapture shell (including thermal protection material) and systems are greater than the propellant required for propulsive capture. Also, aerocapture lends itself to higher velocities since more control authority is available for maneuvers in the arrival planet's atmosphere.

Good sample return opportunities

Sample return missions require several trajectory characteristics. The Earth to Mars trajectory should be a combination of low launch energy (C_3 = 10 or less) and short flight time (one Earth year or less). An adequate stay time of at least 3 months (and sometimes as much as an Earth year) must be available before the return trajectory leg. Finally, the Mars to Earth trajectory must have low launch energy from Mars and a low arrival velocity at the Earth.

Mission architect uses of this data

Propulsive capture case

Aerocapture case

Sample Return case

Conclusions and Future Work

For most missions it is desirable to have the lowest launch energy and arrival velocity possible. Additionally, mission architects want short flight times of less than one Earth year. For some opportunities it is possible to satisfy these general constraints. However, certain opportunities have undesirable high launch energies for the type 1 or 2 trajectories. For these times, it is useful to be able to use a type 3 or 4 trajectory with a lower launch energy.

There are additional constraints placed upon trajectories by sample return cases. Chief among these are the correct phasing between arrival at Mars and return to Earth, and the correct injection conditions at Mars for delivery to Earth. In some cases, Earth-Venus-Mars trajectories provide another option.

Finally, we hope that the enclosed trajectory chart provides mission architects with useful data for years to come. This data will be available on the World Wide Web in the near future. We plan on analyzing future Mars missions in 2007 and beyond over the next several years within the context of the Mars Surveyor Program.

References

1) Interplanetary Mission Design Handbook, Volume 1, Part 2: Earth to Mars Ballistic Mission Opportunities, 1990-2005, Sergeyevsky, Andrey B., Snyder, Gerald C., Cunnif, Ross A., JPL Publication 82-43, September 15, 1983.

2) Mars Exploration Mission Design Data Book for 2015-2026, Knocke, Philip C., Sharma, Jayant, Wolf, Aron, Vaughn, Ramona, JPL Publication D-7278, March 1, 1990.

List of Tools (MIDAS, QUICK papers)

Software used in preparation of this data and paper

FastTrack, version 5.0 for the Macintosh (chart layout)
WordPerfect, version 3.1 for the Power Macintosh

Microsoft EXCEL, version 5.0a for the Power Macintosh
Adobe Photoshop, version 4